Appendix E
Ground Response Analysis to Develop Site-Specific Response Spectra at Soil Sites

E-1. Steps in Ground Response Analysis

This appendix describes one-dimensional ground response analyses, which are often used to modify earthquake motions in bedrock to account for the effects of a soil profile at a site. Steps involved in ground response analyses to develop site-specific response spectra at a soil site are briefly summarized below and are illustrated by an example.

a. Characterization of site conditions. Based on results of field and laboratory investigation programs, one or more idealized soil profiles are developed for the site. Site characterization includes development of dynamic soil properties (e.g., shear modulus and soil damping and their variations with shearing strain) for each soil layer present at the site.

b. Selection of rock motions. Appropriate rock motions (either natural or synthetic acceleration time-histories) are selected or developed to represent the design rock motion for the site. If natural time-histories are used, a suite of time-histories that have ground motion characteristics (e.g., peak ground motion parameters, response spectral content, and duration of strong shaking) generally similar to characteristics estimated for the design rock motions are selected. The response spectra for the selected rock motions should, in aggregate, approximately fit or reasonably envelop the design rock spectrum developed for the site. Natural time-histories may be scaled by a factor to improve the match to the design rock spectrum. If synthetic time-histories (i.e., recorded time-histories modified to achieve a match to a smooth response spectrum) are used, their spectra should approximately fit the design rock spectrum. The duration of shaking should also be reasonable. It is desirable that more than one synthetic time-history be used. Preferably, rock motions are assigned at a hypothetical rock outcrop at the site, rather than directly at the base of the soil profile. This is because the knowledge of rock motions is based on recordings at rock outcrops; and unless the rock is rigid, the motions at the base of the soil profile will differ from those of the outcrop. (The differences increase as the ratio of shear wave velocity of rock to shear wave velocity of soil decreases.) Some computer codes allow the rock motion to be assigned as an outcropping motion.

c. Ground response analyses and development of ground surface response spectra. Using the rock time-histories as input motions, ground response analyses are conducted for the modeled soil profile(s) to compute ground motions at the ground surface. Nonlinear soil response is approximated by either equivalent linear analysis methods (e.g., SHAKE (Schnabel, Seed, and Lysmer 1972), or WESHAKE (Sykora, Wahl, and Wallace 1992)) or nonlinear analysis methods (e.g., DESRA (Lee and Finn 1985) or SUMDES (Li 1990)). Parametric analyses should be made to incorporate uncertainties in dynamic soil properties. Analyses are generally made for best-estimate (average), upper-bound, and lower-bound soil properties. Response spectra of the ground surface motions are calculated for the various analyses made. These response spectra can then be statistically analyzed and/or interpreted in some manner to develop design response spectra of surface motions. The time-histories obtained from the site response analyses can be used as representative time-histories of surface motions. Because the response spectra of the input rock time-histories may not closely match the rock design response spectrum (particularly when natural time-histories are used), it may be desirable to obtain "site amplification ratios" from the ground response analyses rather than using the response spectra of calculated surface motions directly. Site amplification ratios are ratios of the response spectra of the ground surface motions computed from the ground response analyses divided by the response spectra of the corresponding input rock motions. Statistical analyses can be made on the amplification ratios or some other method used to obtain design amplification ratios. The estimated response spectrum at the ground surface is then obtained by multiplying the site amplification ratios by the design rock response spectrum over the entire period range. A design response spectrum is then developed by further smoothing the estimated ground surface response spectrum as required. The time-histories from the ground response analyses can be used directly to represent ground surface motions, or synthetic time-histories can be developed to match the design ground surface response spectrum.

E-2. Example Ground Response Analysis

The procedure described in paragraph E-1 for development of site-specific response spectra at the ground surface of a soil site is illustrated by the example described below. Based on results of field and laboratory investigation programs, the site was idealized by the soil profile shown in Figure E-1. Variations of shear modulus (expressed as the ratio of shear modulus G to the maximum shear modulus G_{max} at a very low strain of 0.0001 percent) and damping ratio with shear strain for clays and for sand were selected as shown in Figures E-2 and E-3, respectively. Three sets of natural time-histories (two components for each set) were selected to represent the design rock motions. Ground response analyses including parametric variations in soil properties were performed. A comparison of response spectra of the computed ground surface motion and the input rock motion for a single analysis is shown in Figure E-4. Typical site amplification ratios computed for average soil properties for three sets of rock motions are shown in Figure E-5. Based on these results, an estimate of site amplification ratios was selected and used to multiply the design rock response spectrum to develop an estimate of the ground surface response spectrum. This spectrum was then smoothed to develop the design response spectrum. The resulting design soil response spectrum is compared with the design rock response spectrum in Figure E-6, which plots the spectral pseudo-relative velocity (PSRV) versus the period.

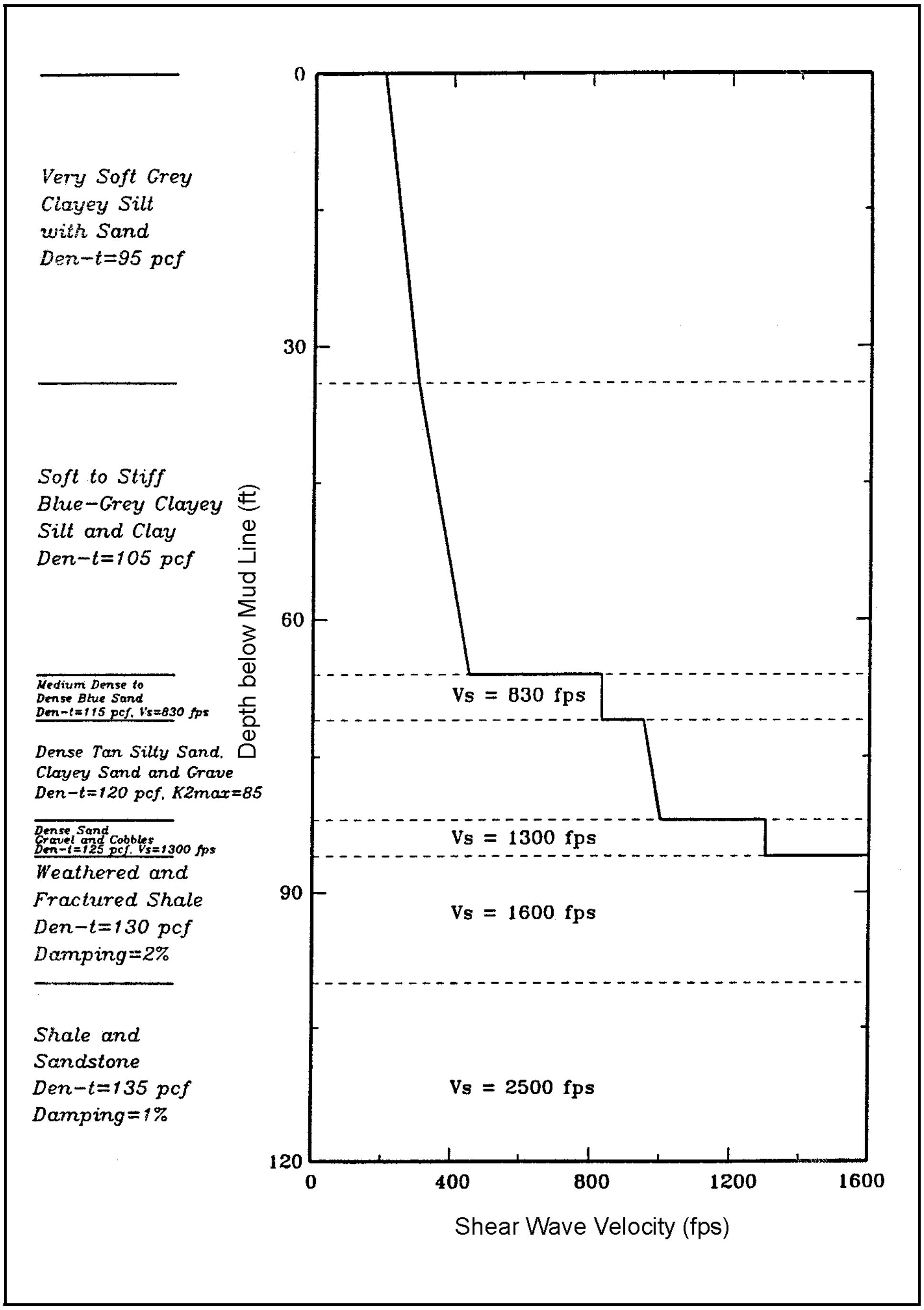

Figure E-1. Estimated shear wave velocity. Note: Den-t = total density; Vs = shear wave velocity; $K2_{max}$ = shear modulus coefficient (1 pcf = 16.02 kg/m^3; 1 fps = 0.305 m/sec)

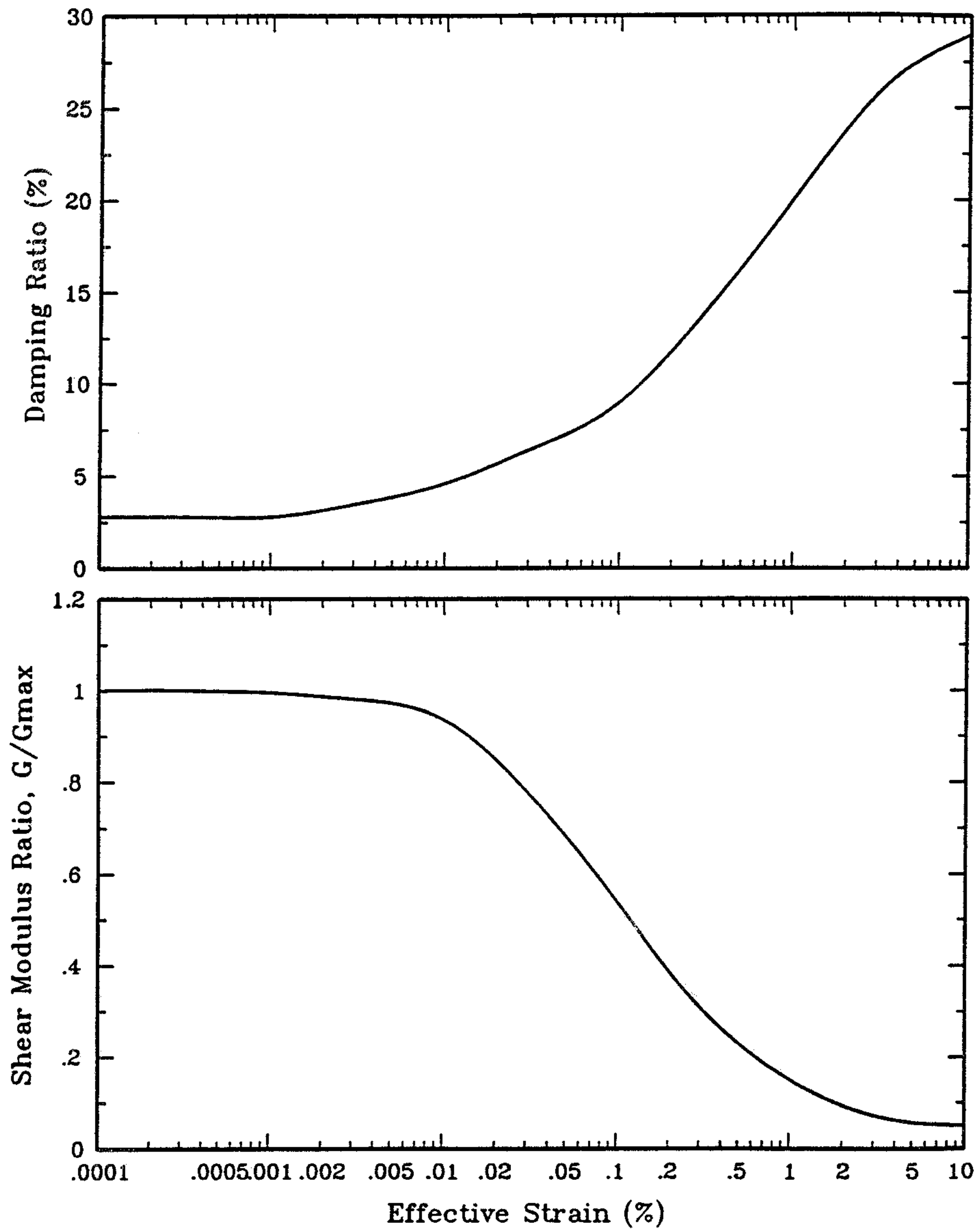

Figure E-2. Variation of shear modulus and damping ratio with shear strain for clays (Seed and Sun 1989, courtesy of Earthquake Engineering Research Center, University of California at Berkeley)

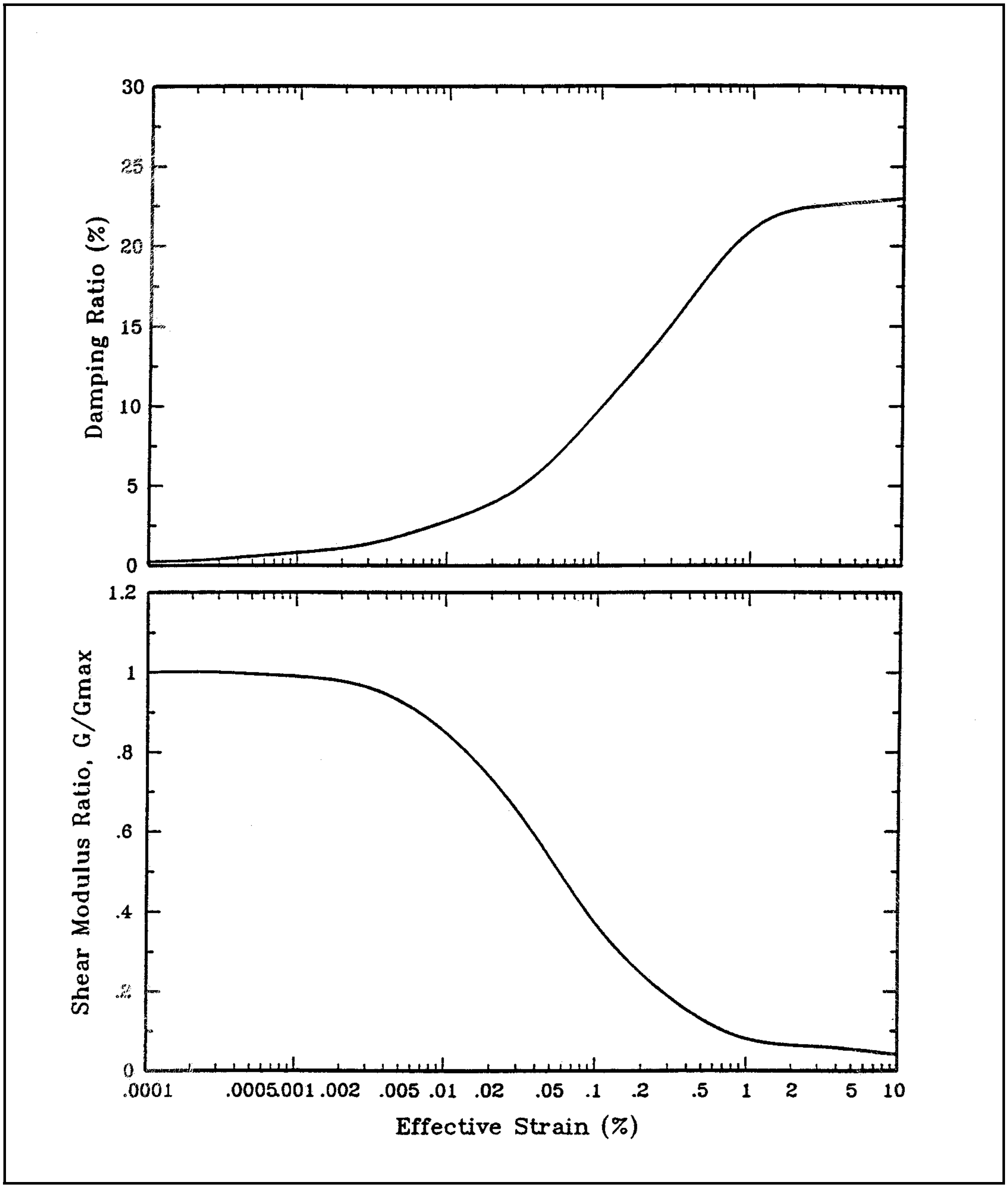

Figure E-3. Variation of shear modulus and damping ratio with shear strain for sand (Seed and Idriss 1970, courtesy of Earthquake Engineering Research Center, University of California at Berkeley)

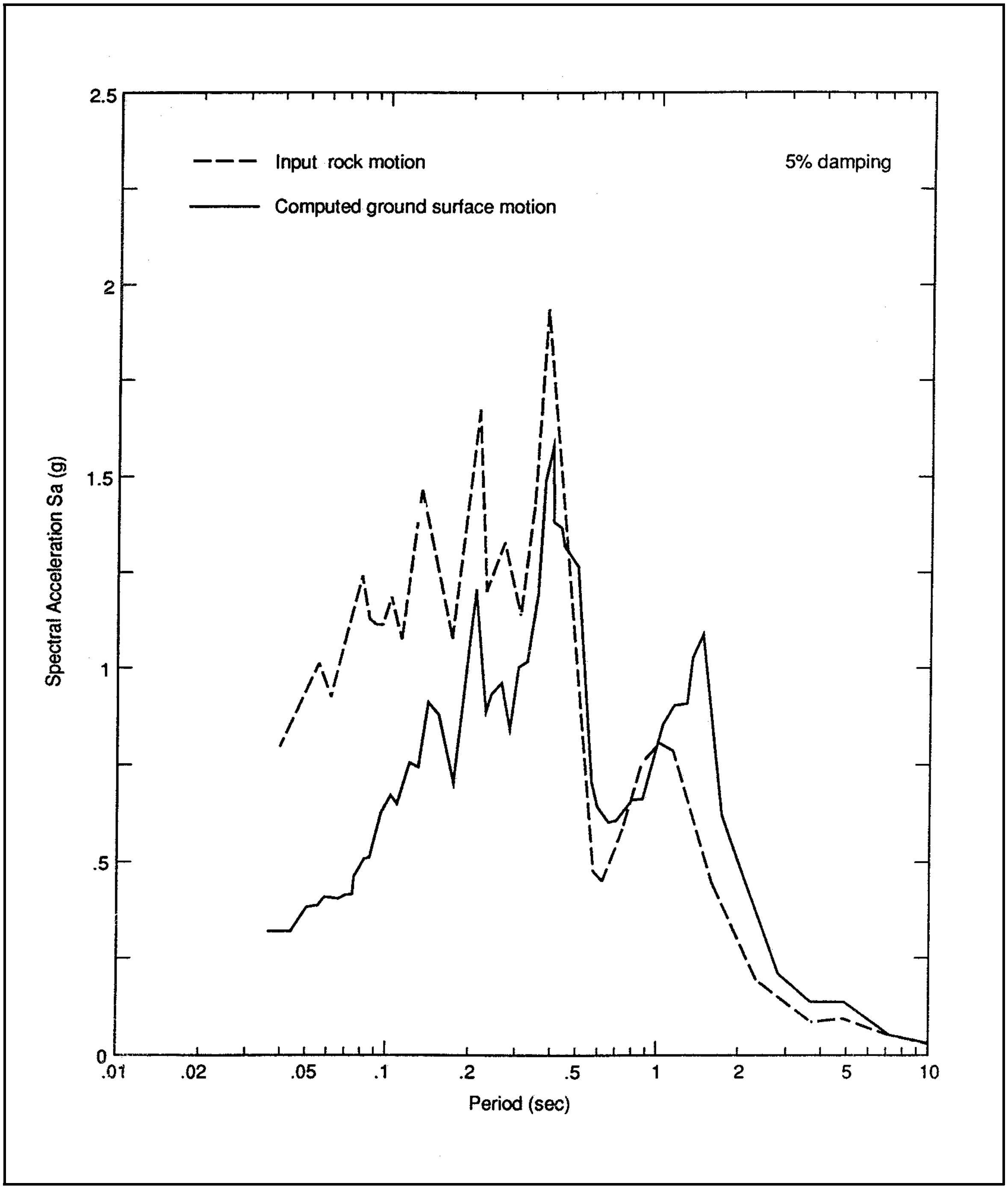

Figure E-4. Comparison of response spectra of computed ground surface motion with input rock motion, average soil properties

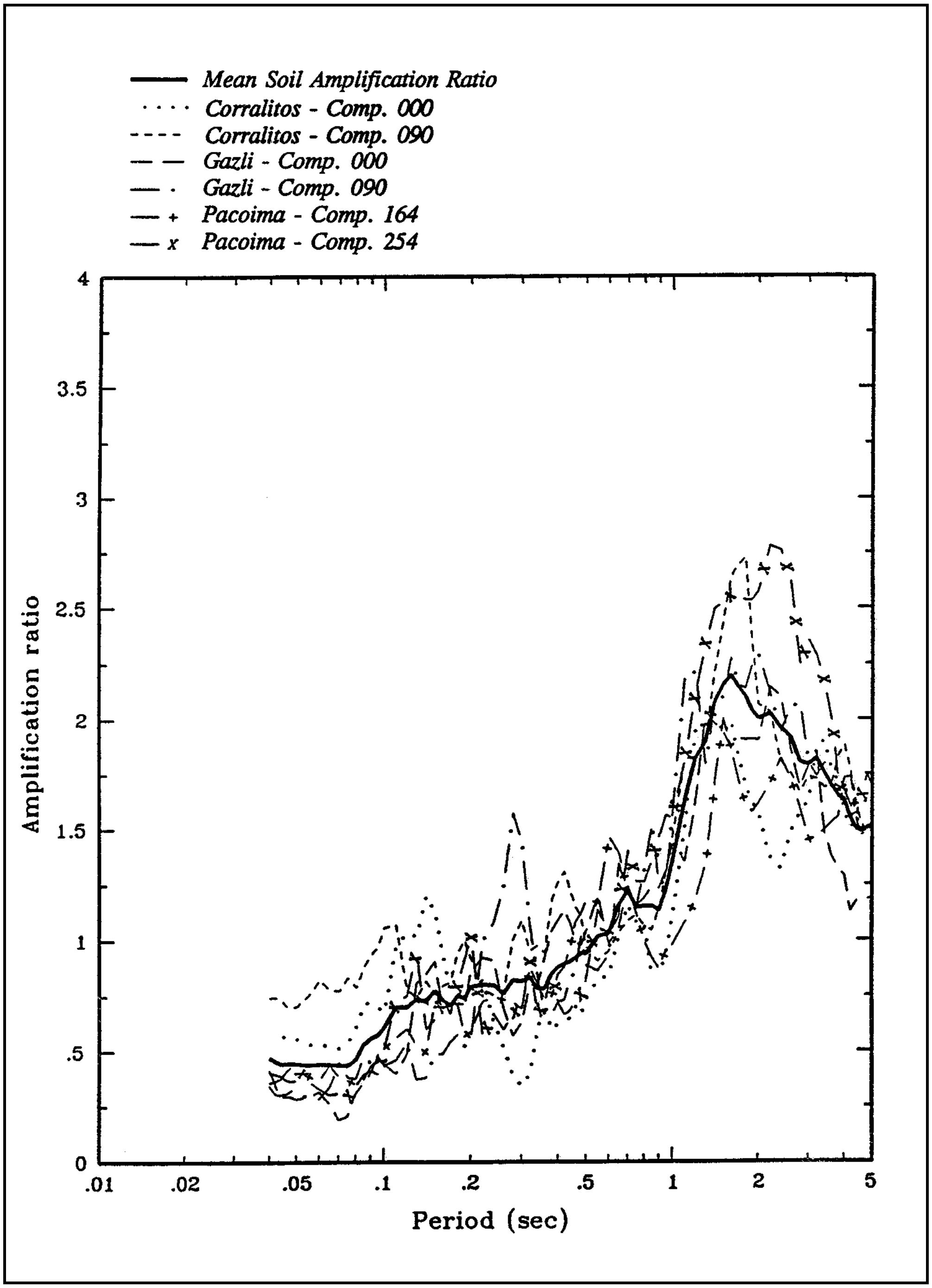

Figure E-5. Soil amplification ratios, average soil properties

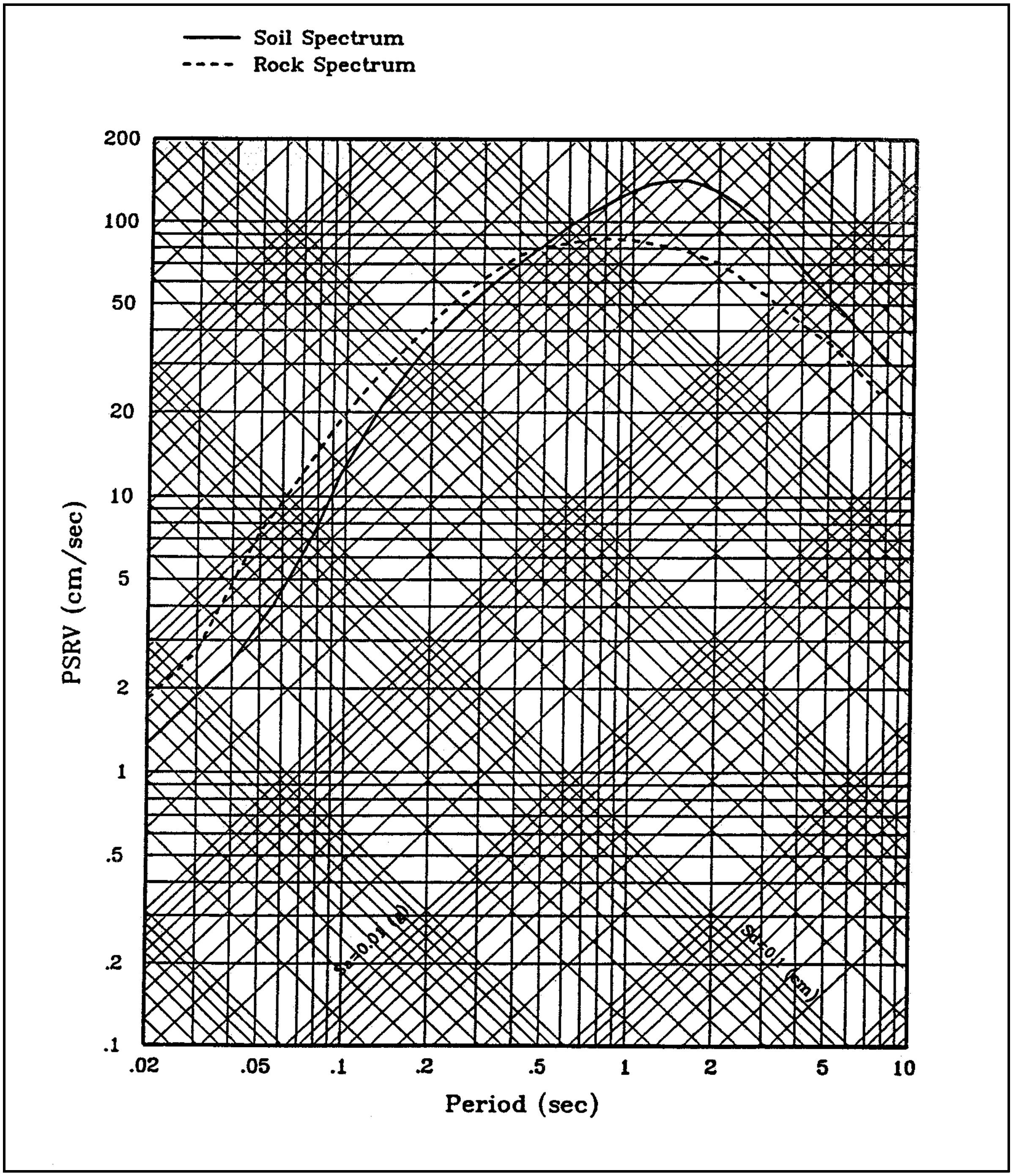

Figure E-6. Median smooth soil spectrum (5 percent damped)